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ScienceDirect
Procedia Engineering 10 (2011) 512–517
ELSEVIER
Engineering Procedia

ICM11

Strengthening Mechanisms of 27MnSiVS6 Microalloyed Steel Deformed by Four Different Forging Processes

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Abstract

The demand of automotive industries for parts with high overall quality, low costs and reduced time to market, forced suppliers to search alternative materials and manufacturing processes. Hot forgings with microalloyed steel represent an extensive application in automotive parts. The main objective of this work was to study the microstructures by transmission electron microscopy (TEM) and mechanical properties of 27MnSiVS6 microalloyed steel deformed by ausforming, warm forging and hot forging. Workpieces were heated for 15 minutes at 1150 ^{0}C before hot forging and 800 ^{0}C before warm forging. Two different ausforming tests were carried out: in the first group workpieces were heated for 15 minutes at 1150 ^{0}C, cooled to 800 ^{0}C at a cooling rate of 8.7 ^{0}C/s and then deformed. In the second group the conditions were kept constant except for the heating temperature of 1000 ^{0}C. All forged products were air cooled after deformed. Ausforming products presented the best mechanical properties. TEM analysis showed that strengthening by vanadium carbonitride precipitates was the main hardening mechanism of both ausformed and hot forged products while warm forgings were strengthened by the higher dislocation density.

Keywords: Metal forming; mechanical properties; hot working.

1. Introduction

Warm forging is widely used in automotive industries [1] to manufacture mild steel components with ferrite-pearlite microstructures [2]. Hot forging is a well-known industrial process and responds for millions of steel components manufactured per year. To obtain a good combination of toughness and

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 doi:10.1016/j.proeng.2011.04.086

strength forgings have to present a refined grain microstructure which depends on the initial grain size, on the forging temperature, and finally on the control of the cooling rate after forging [3]. Ausforging is derived from the ausforming, a thermomechanical processing of high strength steels [4].

The mechanical properties of metallic alloys are strongly influenced by grain refinement which increases the fracture toughness and make some steels superplastic with grain sizes less than 10μm [5]. According to Azevedo et al. [6] the chemical composition presents a negligible effect on the grain refinement if compared to the effect of thermomechanical processes. With small contents of microalloying elements it is possible to produce a significant grain refinement and precipitation hardening as observed in many microalloyed steels [7]. Niobium and Titanium are known for forming strong and fine precipitates in low carbon steels like carbides and carbonitrides which present sizes near to 30 nm, are rectangular and precipitate within the acicular ferrite lamellas when the steel is water cooled after hot deformed. With smaller cooling rates the size of the precipitates increases and they are formed mainly near to dislocations [8].

The main objective of this work is to analyze how four forging processes can improve the mechanical properties of one medium carbon microalloyed steel and what are the strengthening mechanisms.

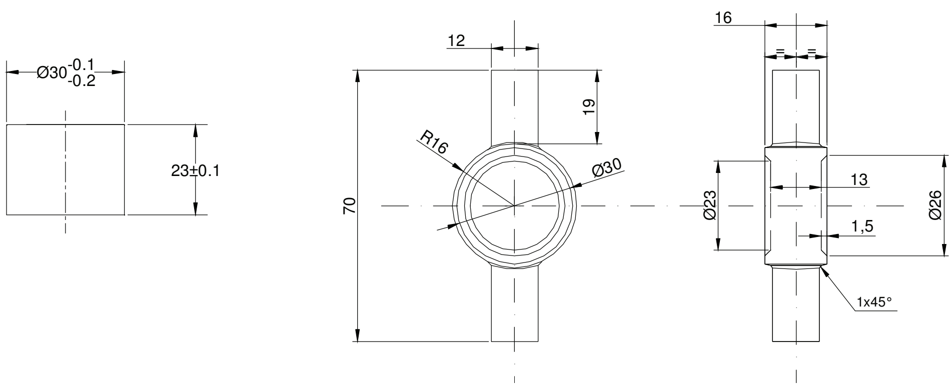
2. Materials and methods

Table 1 shows the chemical composition of the 27MnSiVS6 microalloyed steel studied in this work, a vanadium-titanium microalloyed steel used to manufacture automotive components.

Figure 1 shows the workpiece and the component forged in this work by hot forging, warm forging and ausforging. It is geometry was chosen because it presents a lateral extrusion that permits to analyze the workability and to manufacture samples for tensile and fatigue tests.

Table 1. Chemical composition of the microalloyed steel 27MnSiVS6 (weight %)

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	N	Ti	V
0.310	0.687	1.463	0.010	0.056	0.181	0.006	0.089	0.016	0.016	0.016	0.018	0.111



(a) (b)

Fig.1. (a) workpiece (b) forged component

Table 2 presents the conditions used in the four forging processes. Workpieces were kept for 15 minutes at heating temperature and forging dies were pre-heated at 180ºC.

Table 2. Forging tests conditions

Process	Heating temperature	Cooling rate before forging	Forging temperature
Hot forging	1150ºC	no	1150ºC
Warm forging	800ºC	no	800ºC
Ausforging 1	1150ºC	8.7ºC/s	800ºC
Ausforging 2	1000ºC	8.7ºC/s	800ºC

Cylindrical samples (3mm in diameter, 30mm long) were machined from the forged and air cooled components. Disks 250 µm were cut off those samples, grounded and electrolytic polished to a thickness less than 100 µm to be observed by transmission electron microscopy (TEM) to measure the pearlite interlamellar spacing and the average diameter of precipitates like nitrides, carbides and carbonitrides, and to estimate the dislocation density according to Campos et al. [9], and the volumetric fraction of precipitates according to Morales et al. [10]. With these results it is possible to estimate the contribution of precipitates to the yield strength by the model of Orowan-Ashby, as well the contribution of the interlamellar spacing, ferrite grain size, and ferrite to pearlite proportion [11]. The dislocation density can be used to estimate its contribution to the yield strength by the model of Keh [10].

3. Results and discussion

3.1. Mechanical properties

Statistically the average ultimate strength of ausforging 1 (1099 MPa) is larger than averages of the other three processes. Hot forging presented higher yield and ultimate strength than warm forging (648 and 592 MPa; and 893 and 803 MPa respectively). Ausforgings 1 and 2 presented the higher average yield strength (720 and 716 MPa respectively).

3.2. Contribution of precipitates to the yield strength

Table 3 presents the volumetric fraction, the average size of the precipitates and their contribution to the yields strength. Figure 2(a) shows some dislocations and vanadium carbonitrides observed in a hot forged sample. The difractogram of the precipitates is shown in Figure 2(b). The carbonitrides probably precipitate only within the austenite grains because the high forging temperature and strain rate, and contributed significantly to the yield strength as previously observed [9] and [10].

Table 3. Contribution of carbonitrides to the yield strength

Process	Density per volume (nm^{-3})	Volumetric fraction(Fv)	Precipitate diameter (nm)	Contribution to the yield strength (MPa)
Hot forging	3.47471E-05	0.000780	3.50 ± 0.71	150.07
Warm forging	1.18261E-05	0.000572	4.52 ± 1.01	114.11
Ausforging 1	2.26337E-05	0.001116	4.55 ± 1.21	158.90
Ausforging 2	6.07473E-06	0.001082	6.98 ± 1.47	123.74

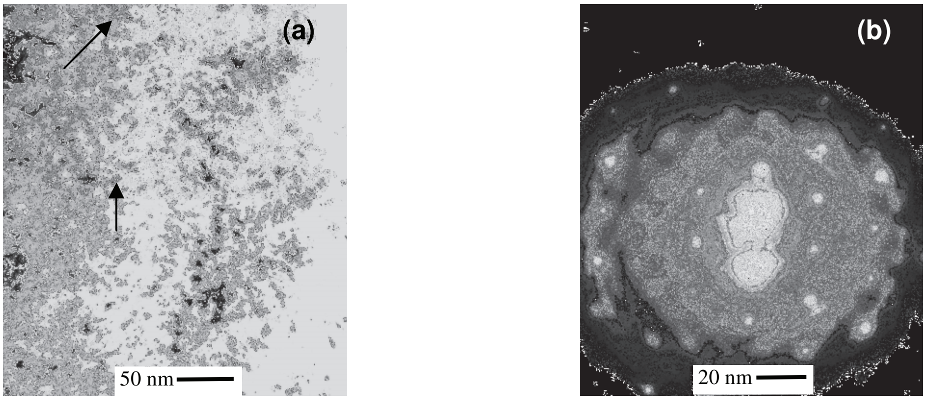


Fig. 2. Hot forging sample: (a) carbonitrides precipitation (TEM); (b) precipitates difractogram (TEM)

Figure 3 shows the carbonitrides present within the warm forged component. It is likely that the precipitation was predominantly between ferrite and pearlite phases because the steel was heated and deformed at 800ºC below the temperature for complete austenitization (Ac_3). It can be assumed that dislocations and Ti precipitates were the main sites to the precipitation of very refined carbonitride as also observed by Ghosh and Chatterjee [12] in Ti-Nb microalloyed steels.

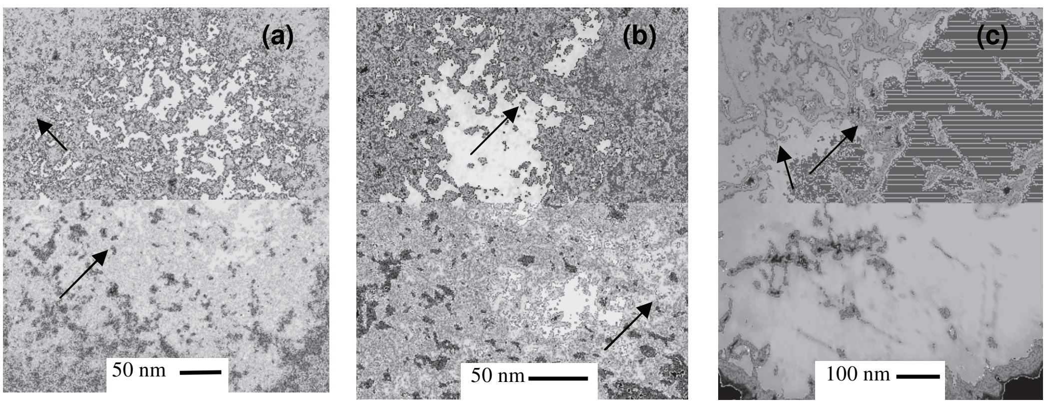


Fig. 3. Carbonitrides precipitation (TEM): (a) warm forging; (b) ausforging 1; (c) ausforging 2

3.3. Dislocation density within the ferrite grains

As observed in Table 4 warm forging presented the higher dislocation density and consequently the higher contribution to the yield strength. The other three processes presented similar densities and contributions.

3.4. Contribution of interlamellar spacing and microstructure to the yield strength

Table 5 presents the pearlite interlamellar spacing (Figure 4) and its contribution to the yield strength, defined as basic because strengthening caused by precipitation and dislocation density was not yet considered. Hot forging presented the lower ferrite fraction, i.e., among the four processes hot forging presented the higher fraction of pearlite, and although it presented the larger pearlite interlamellar spacing, its higher pearlite fraction contributed to increase the yield strength.

Table 4. Dislocation density contribution to the yield strength

Process	Dislocation density (cm^{-2})	Contribution to the yield strength (MPa)
Hot forging	7.06E+10	55.84
Warm forging	1.61E+11	84.14
Ausforging 1	6.17E+10	51.72
Ausforging 2	6.03E+10	51.57

Table 5. Interlamellar spacing and ferrite fraction contributions to the yield strength

Process	Interlamellar spacing (nm)	Ferrite fraction (%)	Contribution to the yield strength (MPa)
Hot forging	99.56 ± 26.47	37.12 ± 0.49	501.20
Warm forging	61.03 ± 10.35	59.64 ± 1.53	498.00
Ausforging 1	70.95 ± 18.87	62.95 ± 4.70	474.04
Ausforging 2	88.21 ± 22.71	55.23 ± 1.65	473.04

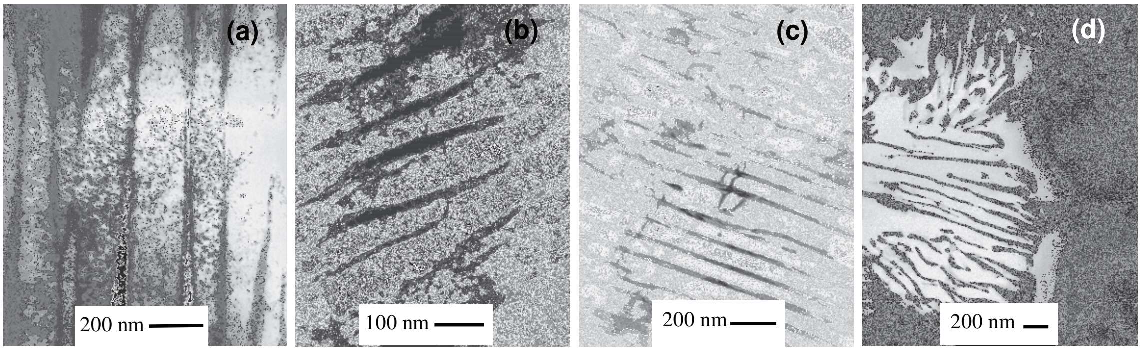


Fig. 4. Pearlite interlamellar spacings: (a) hot forging; (b) warm forging; (c) ausforging 1; (d) ausforming 2

3.6. Cumulative effect of hardening mechanisms

The yield strength calculated from the tensile tests can be assumed to be a sum of contributions of each hardening mechanism [9]. The difference between the cumulative yield strength, i.e. the sum of all contributions, and the tensile yield strength is less than 10% for all the forging process, except for the warm forging which presented a difference of 17.7% explained by the small size of the sample that made difficult to evaluate the precipitates contribution, since the strengthening by the interlamellar spacing and density dislocation in all the four processes agreed with previously reported results [9] and [10].

In this work the increase of the mechanical strength in hot forging was caused by the refinement of the ferrite grains, by the high dislocation density and by the carbonitride precipitation, as discussed by Bakkaloglu [3], and by the higher pearlite fraction as also observed by Matlock et al. [13]. In ausforging 1 besides those mechanisms, the presence of acicular ferrite favored the strengthening.

4. Conclusion

Four forging processes were evaluated in respect to the increasing of the mechanical strength of the microalloyed steel 27MnSiVS6. Statistically the average ultimate strength of ausforging 1 is larger than averages of the other processes. Hot forging presented an average higher than warm forging. Ausforging 1 and 2 presented the higher average yield strength, and again hot forging presented a higher strength than warm forging. Ausforming 1 presented an average elongation greater than warm forging and Ausforging 2 and hot forging presented statistically the higher average elongation.

The higher pearlite fraction was the most influent contribution to the strengthening during hot and warm forging which also presented an important contribution of the dislocation density.

Carbonitrides were more significant to the strengthening during hot forging and the most significant factor to strengthening products forged by ausforming, if compared to dislocation density contribution.

Acknowledgments

Authors thank CNPq (Brazilian Council for Scientific and Technological Development) and FAPESP (Foundation for Researchers of the State of Sao Paulo) for the financial support.

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